Design, Fabrication, Testing and Validation of a Ruggedized Fiber Optic Sensing System (FOSS) for Launch Application

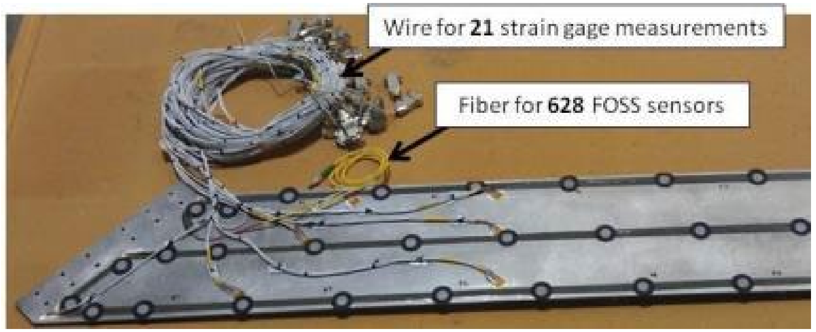
AIAA Science and Technology Forum and Exposition

Peacock Spring, SENS-03

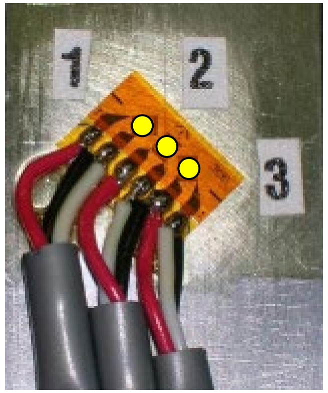
Thurs, Jan 11th, 2024

Why Choose Fiber Optic Sensors over Resistive Gages?

One Of These Things (is Not Like The Others)

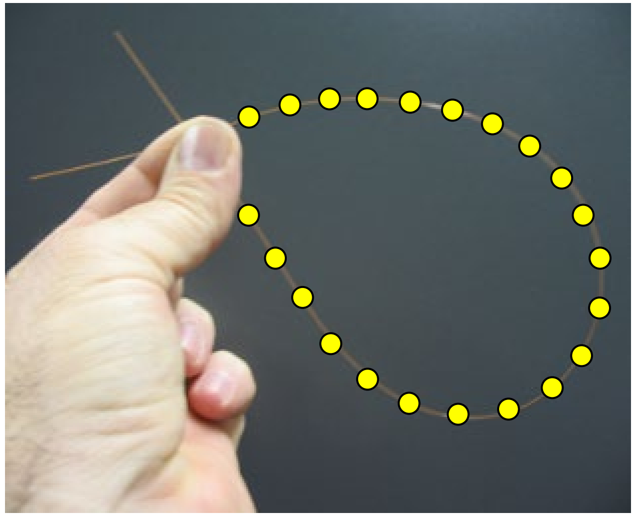


(Heavy)



(Big)

(Hard)

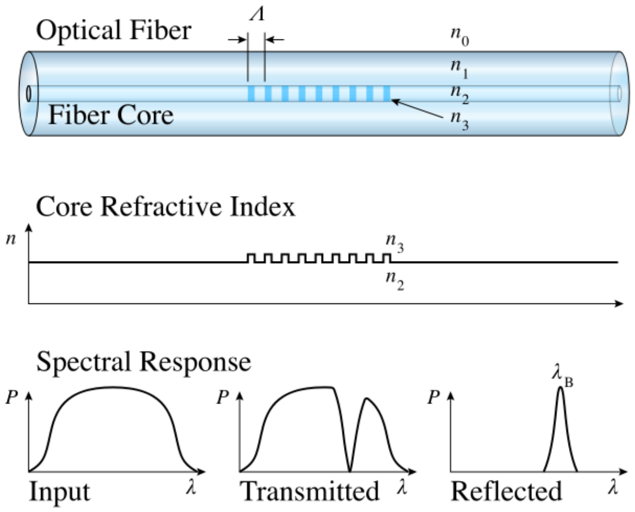


(Light, small, easy)

Fiber Bragg Grating (FBG) as sensor

Principle

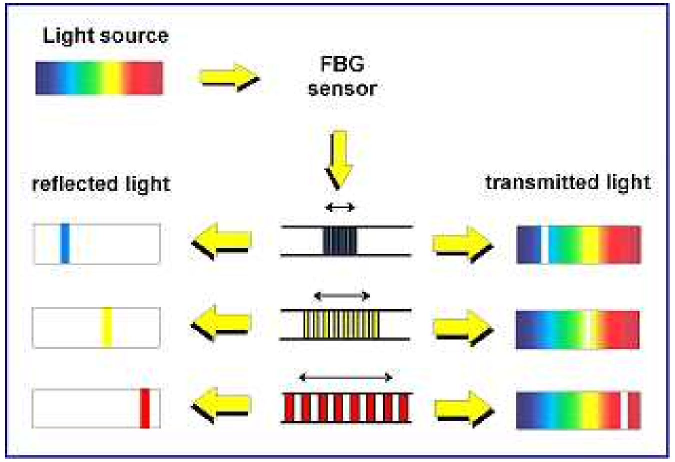
- Fiber Reflector that reflects a particular wavelength and transmit all others
- Bragg Wavelength: λ_B=$2n_e\Lambda$



Measuring Strain(ε) or Temperature (ΔT) via FBG sensor

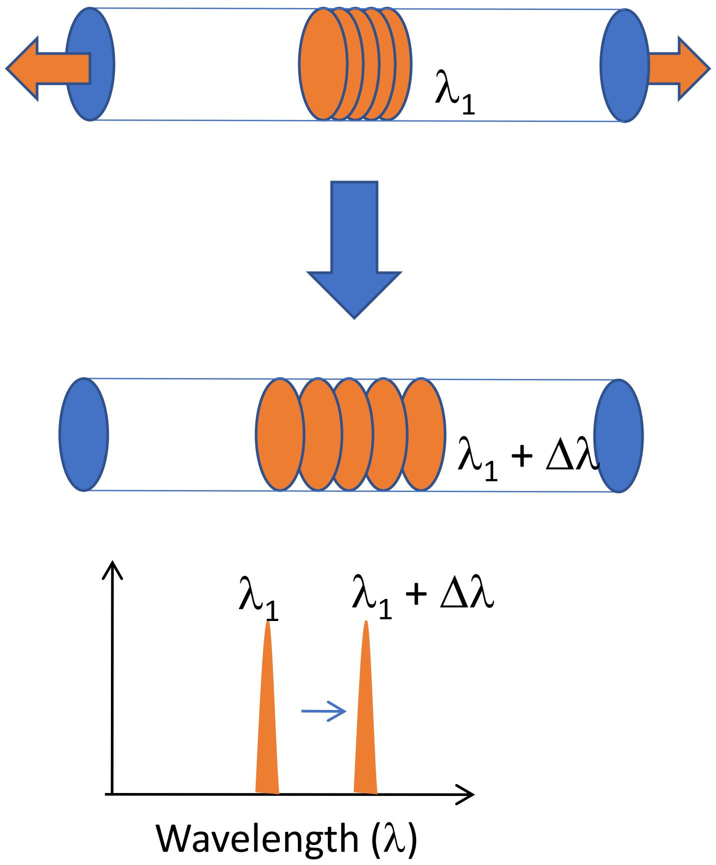
$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon + (\alpha_\Lambda + \alpha_n)\Delta T$$

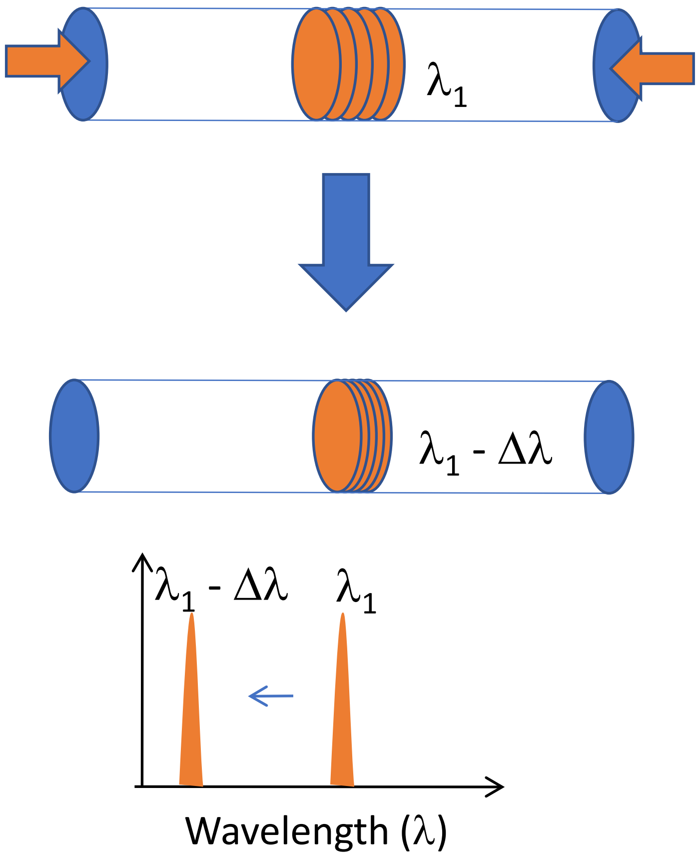
- $\Delta\lambda_B$= change in Bragg wavelength <u>due to environmental change</u>
- λ_B= Initial Bragg wavelength of FBG
- p_e= strain-optics coefficient
- α_Λ = Thermal expansion coefficient
- α_n = thermo-optic coefficient



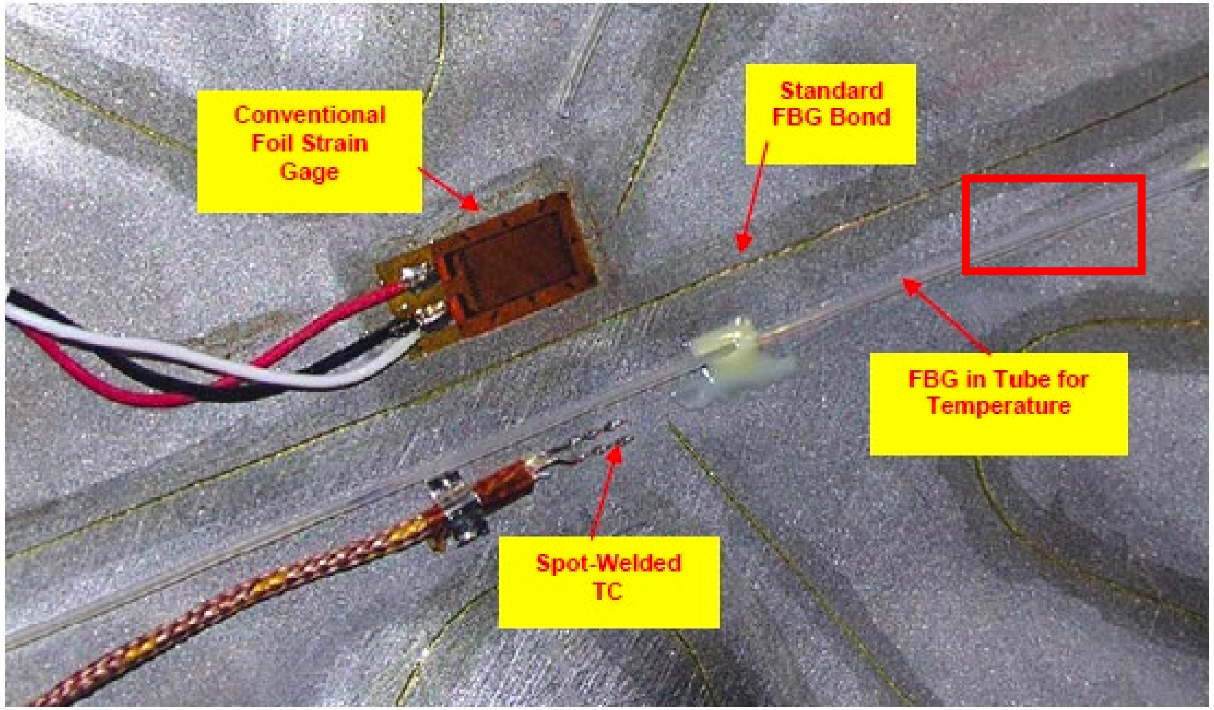
How do FBG sensors works?

- Like an accordion → change in Bragg Wavelength

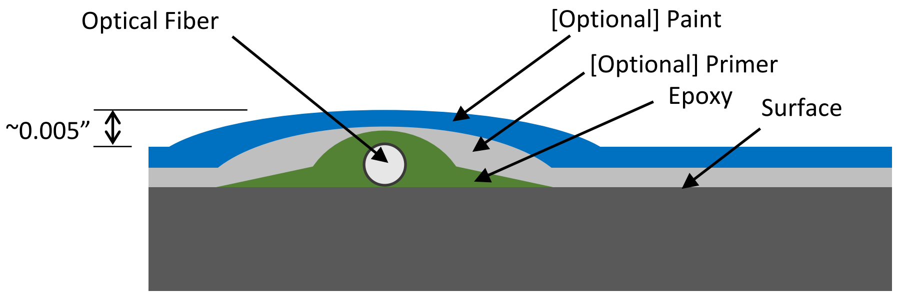




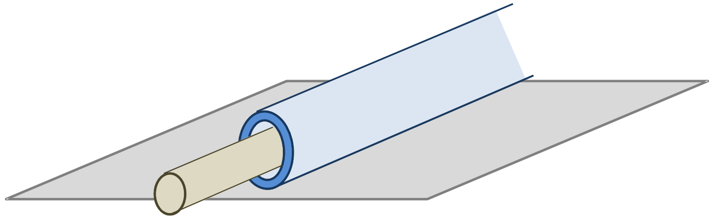
How to implement FBG into structural health monitoring (SHM)



Side-by-side comparison of fiber-based strain and temperature sensor vs convention foil-type strain gage and thermocouple



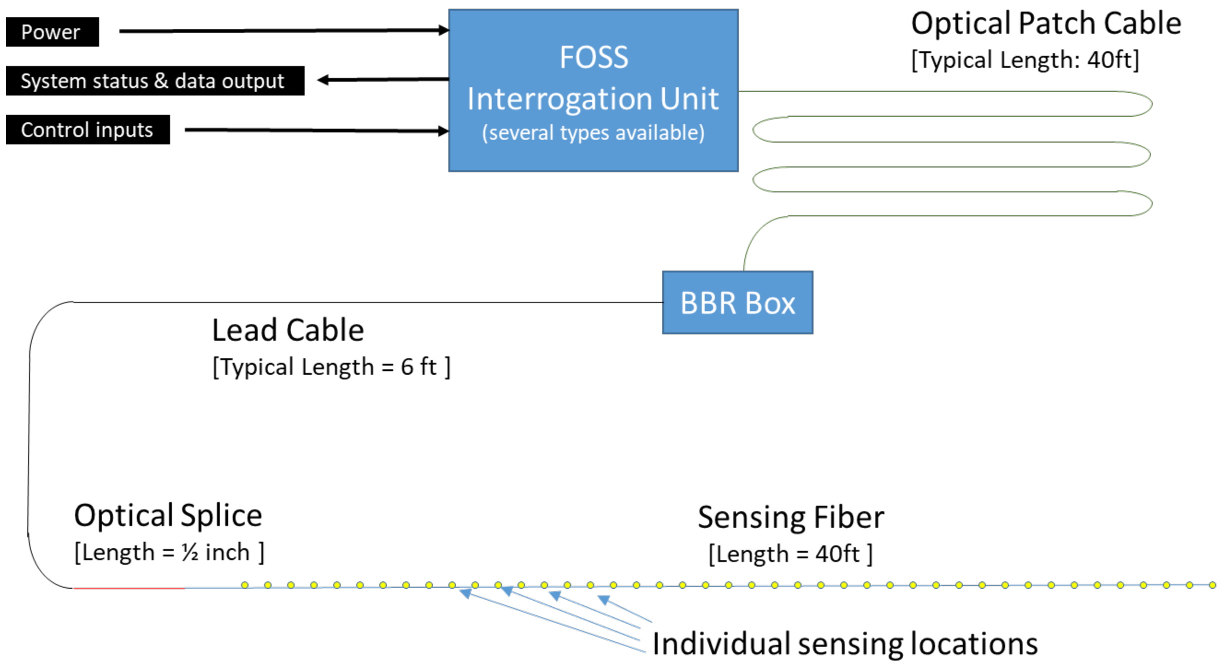
Layers of optical fibers for strain bonding.



An FBG being loosely coupled to measure temperature without measuring mechanical strain generated from the surface.

NASA's Unique FBG Interrogation Technique: OFDR

- Optical Frequency Domain Reflectometry (OFDR):
  - Based on laser interferometry
    - Single Longitudinal mode laser needed
  - Involves signal processing
    - Fourier Transform/inverse Fourier Transform
  - Use weak reflectivity FBG
    - Typical WDM FBG's R=80%
    - Typical OFDR FBG's R=0.05%
  - So why use OFDR for sensing instead?
    - Thousands of sensors in 1 single fiber
    - High spatial density (sensor every ½" increment)

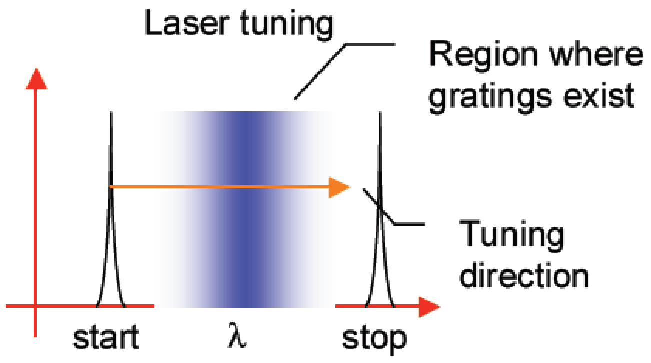


Optical Frequency Domain Reflectometry

- All FBGs are written at the same wavelength (λ_B), instead of each having a unique wavelength (WDM)
  - Multiplexing of hundreds of sensor in single fiber
- A narrowband wavelength tunable laser source is used to interrogate multiple sensors.
- Each FBG sensor <u>is only ½ inch long</u>

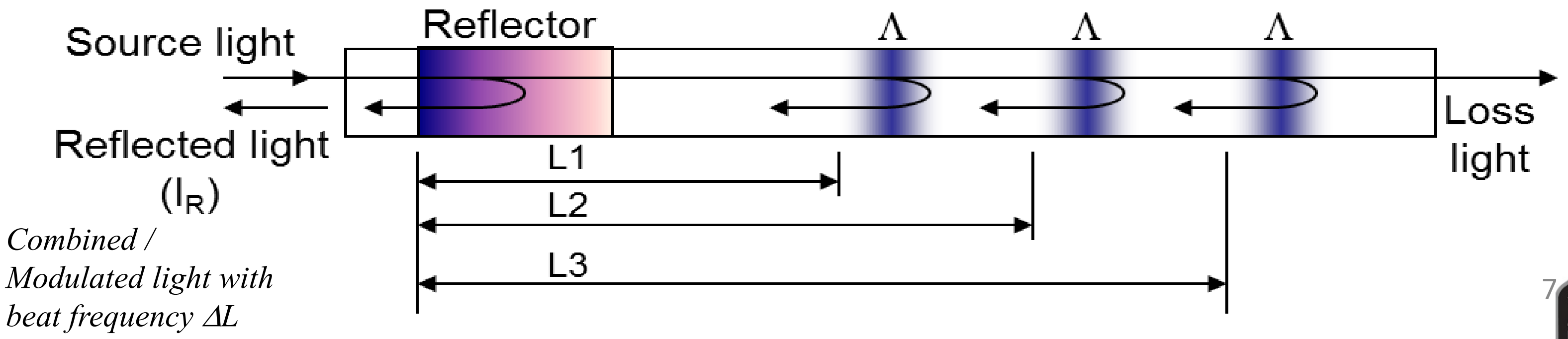
Principle

- Combine 2 coherent waves to generate a beat frequency
  - This is an unique beat frequency based on the length difference ΔL
- Multiple sensors with unique beat frequencies (ΔL_{fbg}) are captured
- In Fourier Domain each sensor with unique frequency is separated, and iFFT to obtain its design wavelength (λ_B)

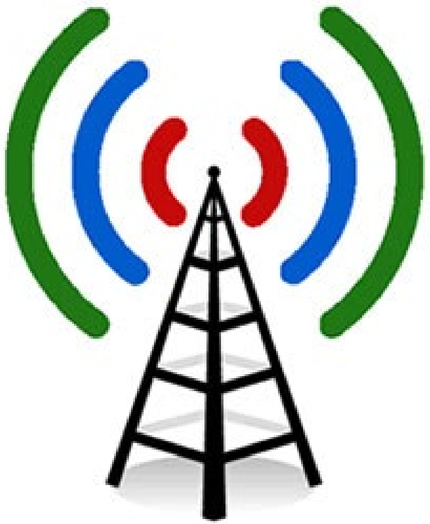


$$I_R = \sum_i R_i Cos(k 2 n_0 L_i) \qquad k = \frac{2\pi}{\lambda}$$

R_i – spectrum of i^{th} grating
n_0 – effective index
L – path difference
k – wavenumber



Layman’s Term: Tuning your favorite radio station!

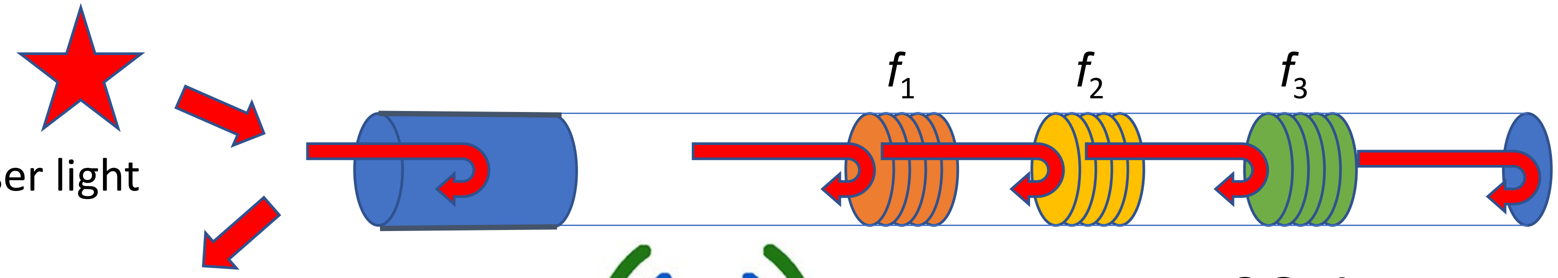


Multiple frequencies
are broadcasted on airwave

Radio receives ALL frequencies

Radio tuner accepts ONE frequency

Radio analogy to Optical Frequency Domain Reflectometry



Laser light

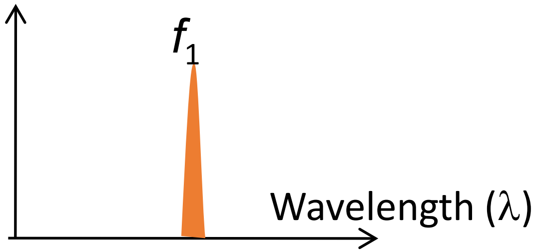
Photo-detector

(Receive ALL sensor signal)

97.3 97.7 98.1

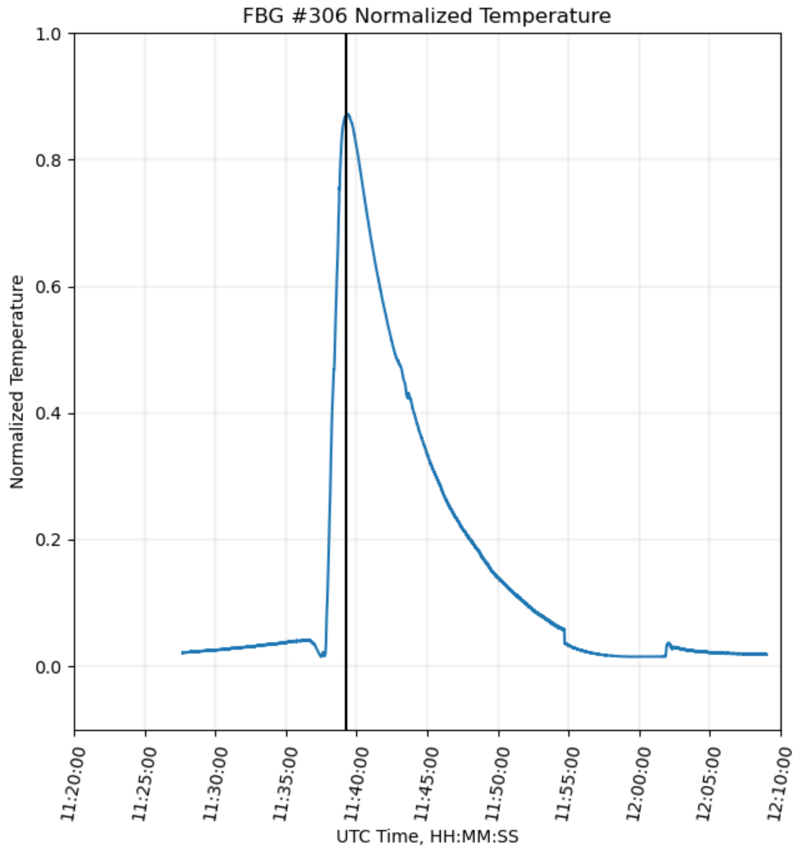
Sensor Frequency ID
(Broadcast Tower)
Determined via location of sensor

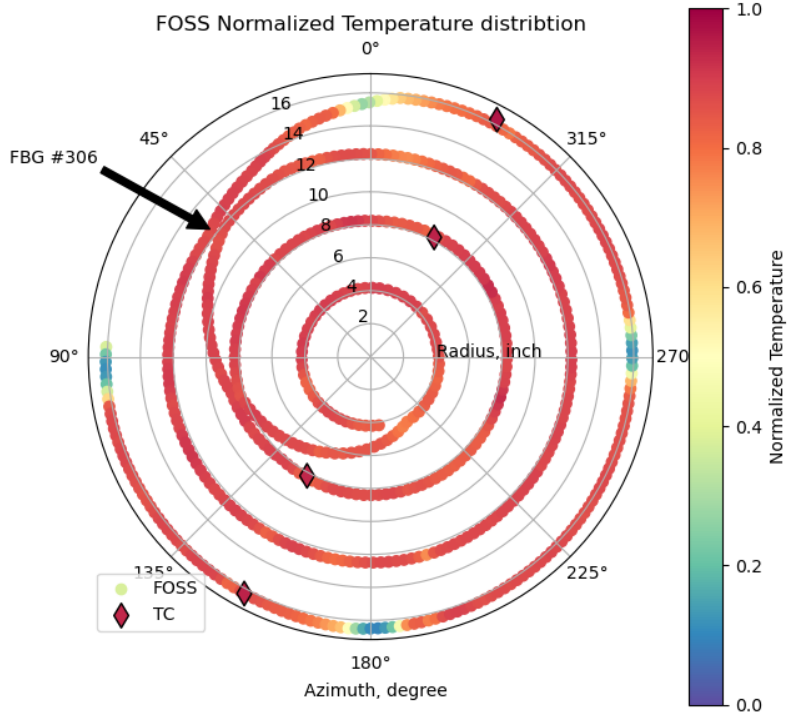
(Radio Receiver)

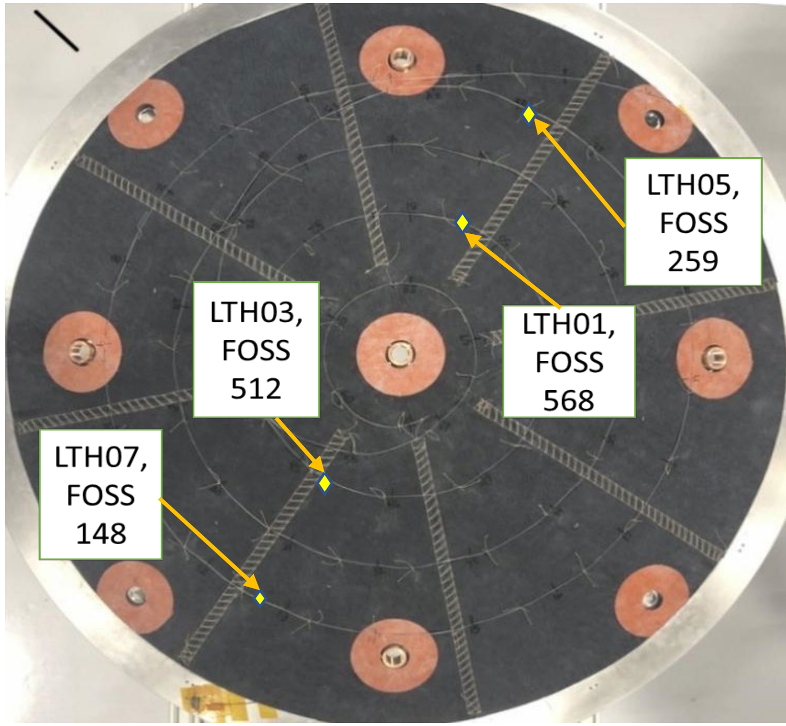


FFT/iFFT to "dial in" to particular sensor information
(Radio Tuner)

Advantage of FOSS – LOFTID results

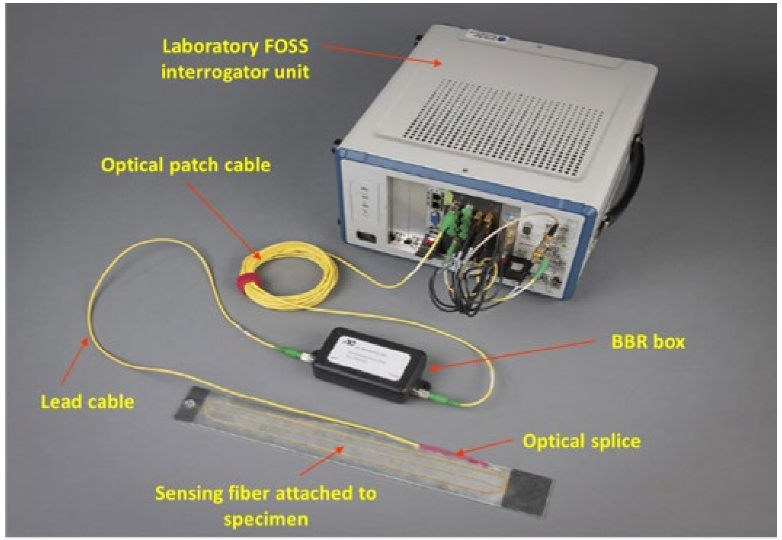


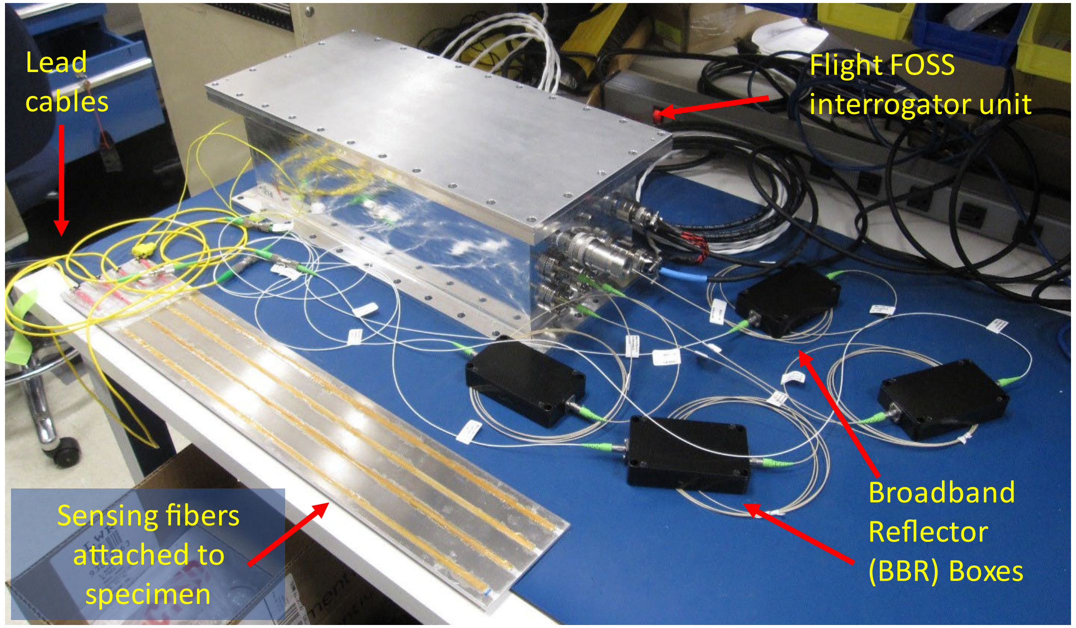




Four thermocouples (diamond) vs 1000+ FBG data gives high spatial density temperature information of rigid nosecone during re-entry

Comparing laboratory FOSS vs launch-capable FOSS system



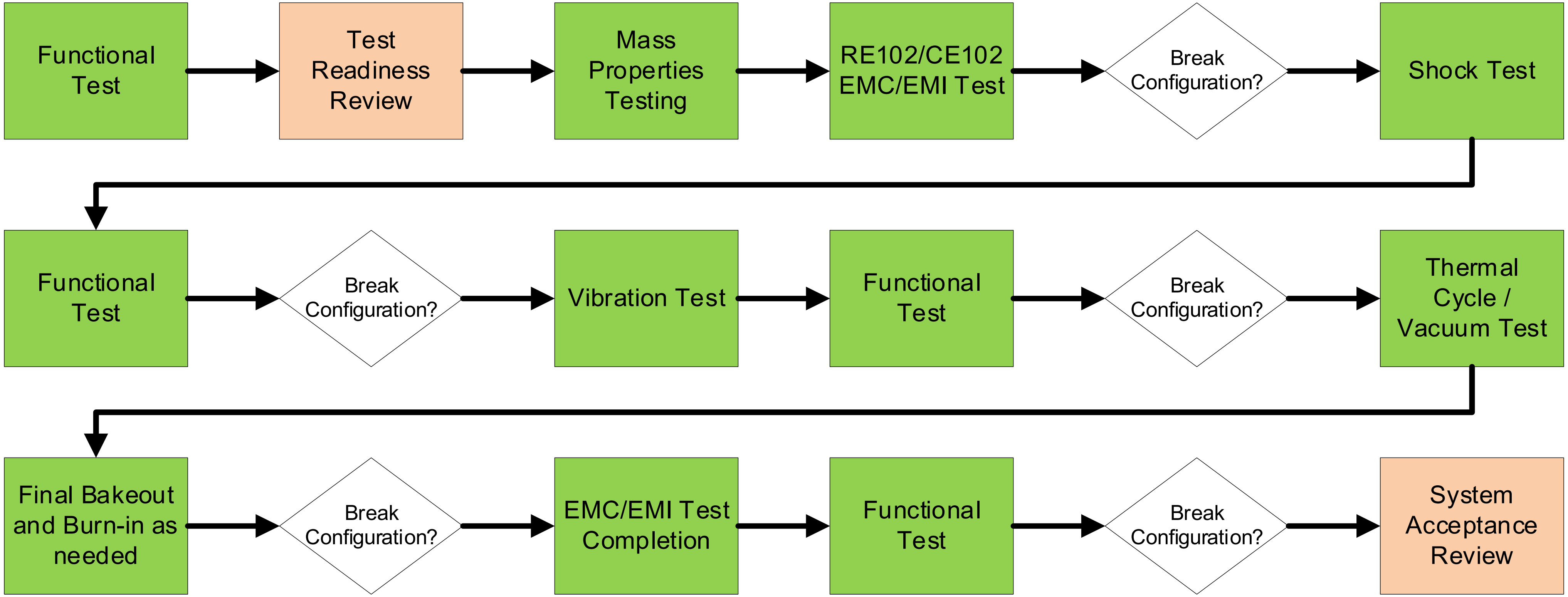


Launch Capable FOSS Specifications	
Parameters	**Units**
Fiber channel count	4
Max sensing fiber length	40 ft
Max patch cable length from system	≈100 ft
Fiber type	Single-mode fiber (SMF)-28
Max no. of sensors/fibers	2,000
Max Sample rate	50 Hz
Onboard storage	32 GB
Interface	Gigabit Ethernet
User Interface Protocol	transmission control protocol (TCP)/internet protocol (IP)
Operational Communication Protocol	user datagram protocol (UDP)
Power	70 W at 28 VDC
Weight (including enclosure)	38 lbs
Size (application specific)	18.15 in by 8.625 in by 6.25 in

FOSS ruggedized units, prior to environment testing

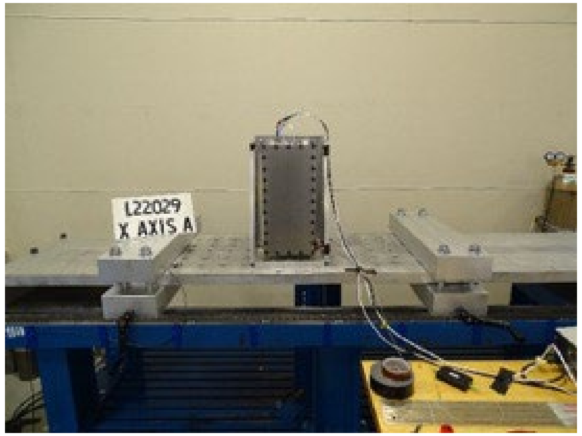
[4] identical units are built for environmental testing, where:
1 unit = Qualification unit
1 unit = Integrated into LOFTID
2 units = spares, later becomes proto-qualified units

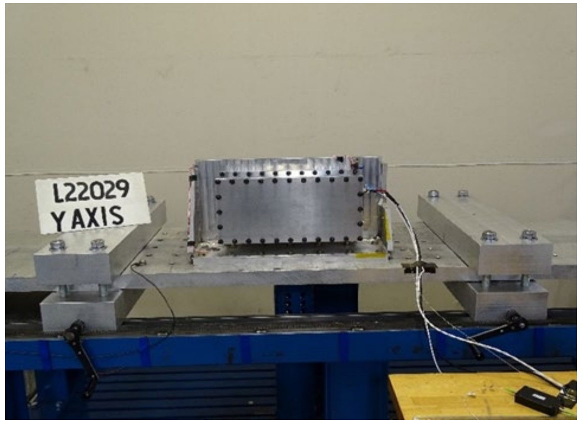
Environmental Testing Protocol to Certify FOSS for flight



FOSS integration and test plan to follow, to make sure unit does not break any baseline configuration

FOSS under pyroshock testing - Summary



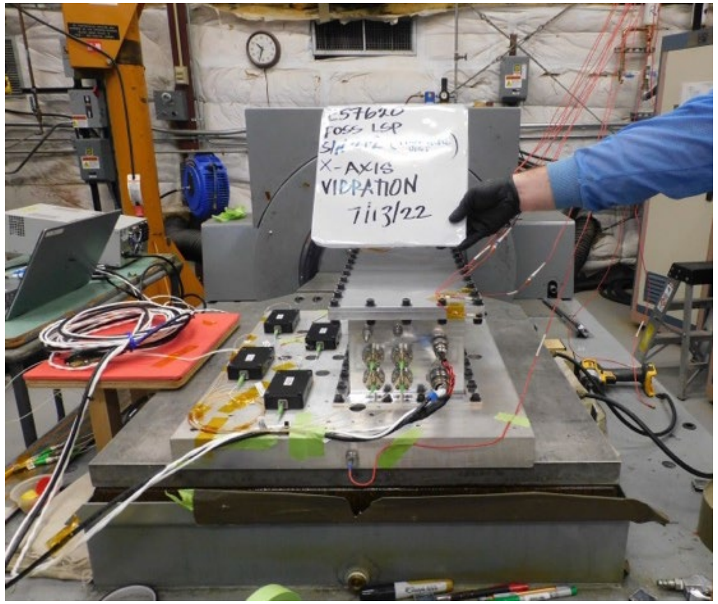


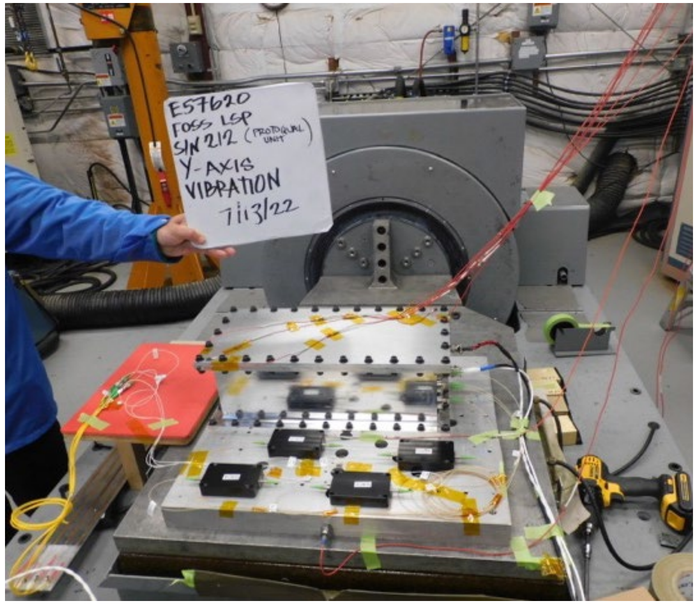
Shock Test	# Shocks in Each Direction			Components	Results
	X	Y	Z		
1st	3	0	0	Full system test	Optical network failure. Mounts replaced after test.
Optical Network	3	3	3	Subcomponent test	Fully operational through all shocks. Component passed.
2nd	3	3	3	Full system test	Optical network failure. Completed remaining axis. Rest of system was operational after 9 shocks.
BBR	3	3	3	Subcomponent test	All three directions tested at once. Result Pass
Delta Qual	4	3	3	Full system test	Carrier board short on shock 7 during testing. Rest of system was operational after 10 shocks.

Lesson learned about integrating optical network into a shock environment

PS – next iteration of optical network does not have a fan anymore

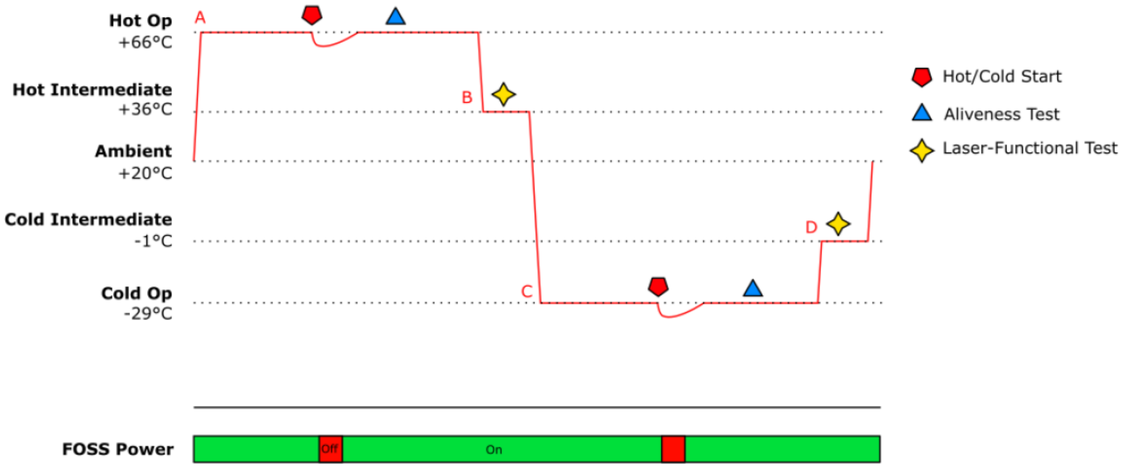
FOSS under random vibration testing - AFRC





- Testing - July 2022
- During qualification level, swept source laser within unit failed due to over-testing during shock (which it endures 22 shock events)
- Proto-qualification level was used (3dB above envelope of MPE, max predicted environment)
    - 2 units passed random vibration in all x-, y- and z-axis, with 11 GRMS under 2 minutes

FOSS under thermal cycling testing - KSC

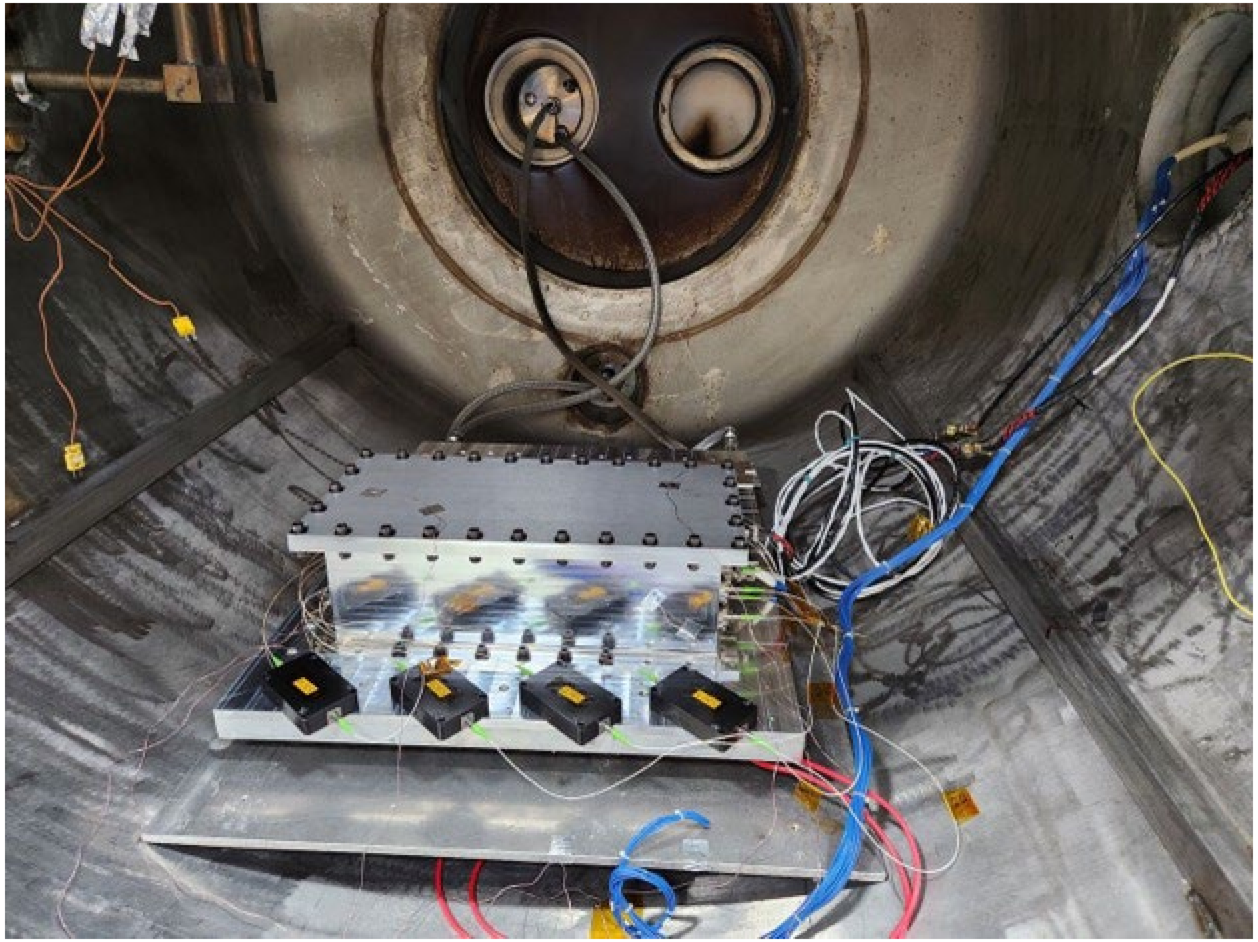


Plateau	Temperature	Plateau Duration	Tests
A	66 ºC ±3 ºC	270 min	FOSS Aliveness
B	36 ºC ±3 ºC	120 min	FOSS Functional
C	-29 ºC ±3 ºC	270 min	FOSS Aliveness
D	36 ºC ±3 ºC	120 min	FOSS Functional

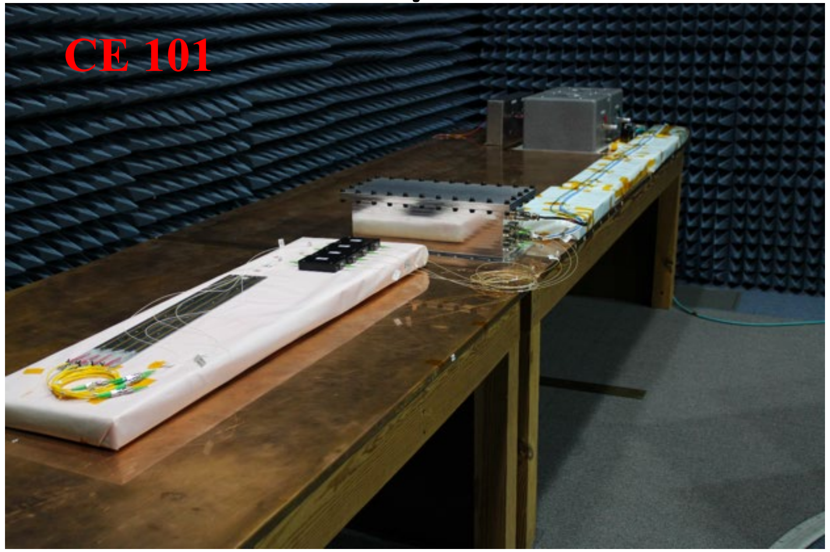
- 16 consequent cycles conducted – takes 7 days continuously
- One of the 2 proto-qualified unit failed – laser controller electronics failure
- One unit was shipped to LaRC for thermal vacuum cycle testing

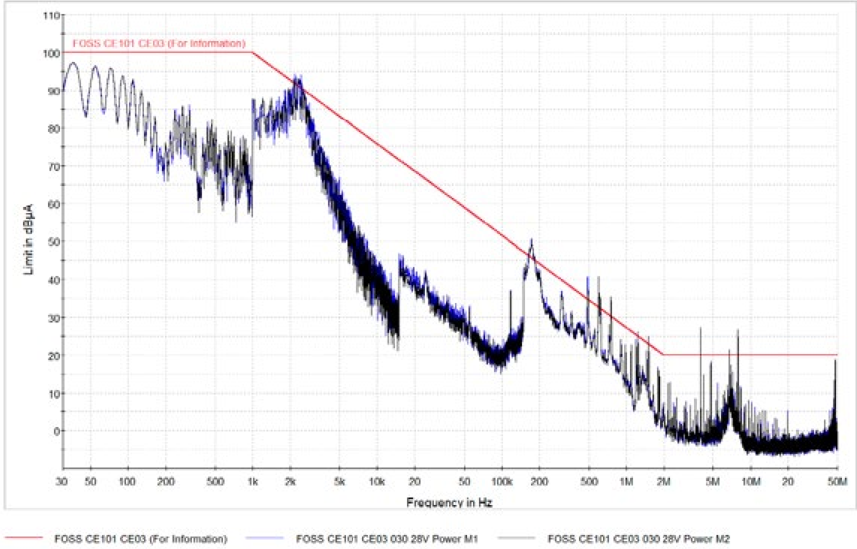
FOSS under thermal vacuum cycle testing - LaRC

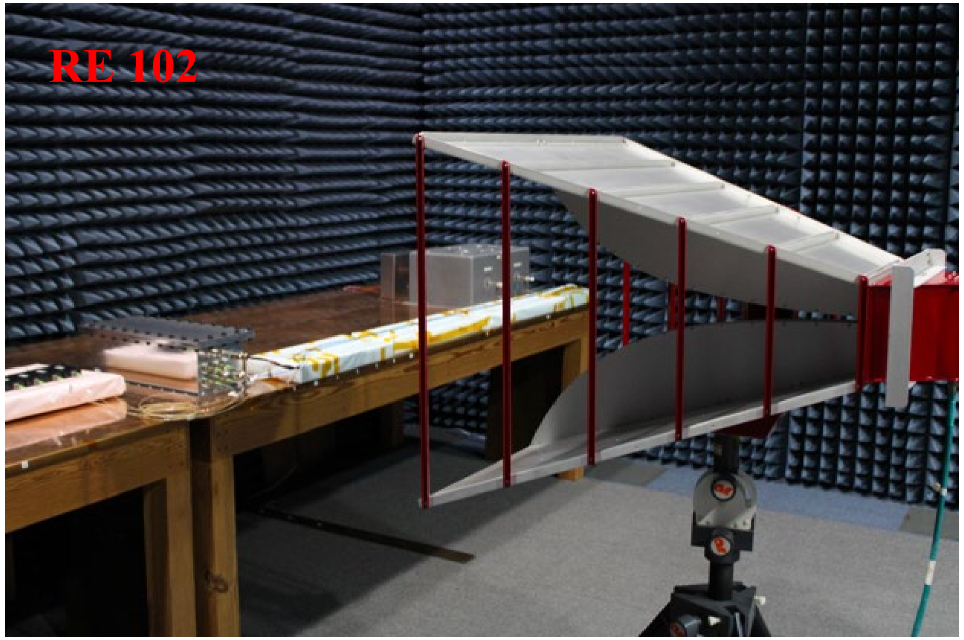
- Testing from Sept 12-15, 2022
- 4 thermal cycles, identical to previous test, but in additional, under vacuum (< 10×10^{-4} Torr) condition
- FOSS unit passed all thermal-vacuum testing

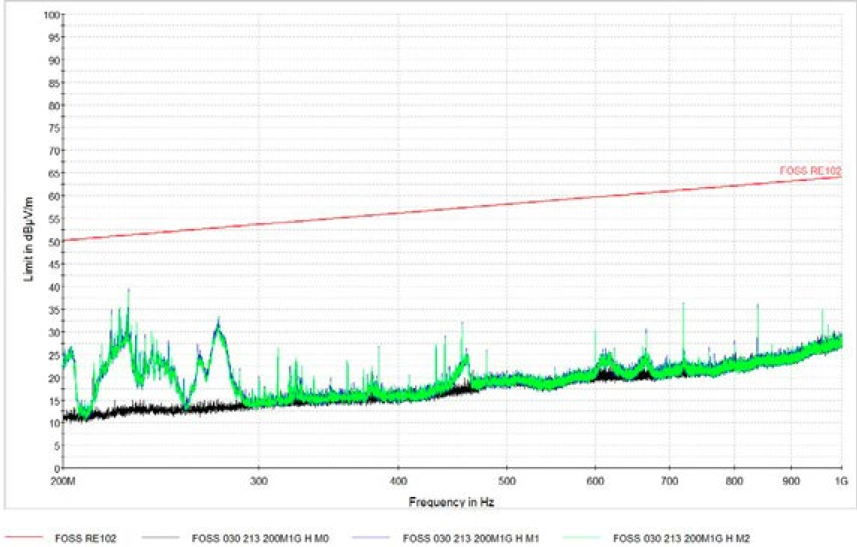


FOSS under EMI/EMC testing

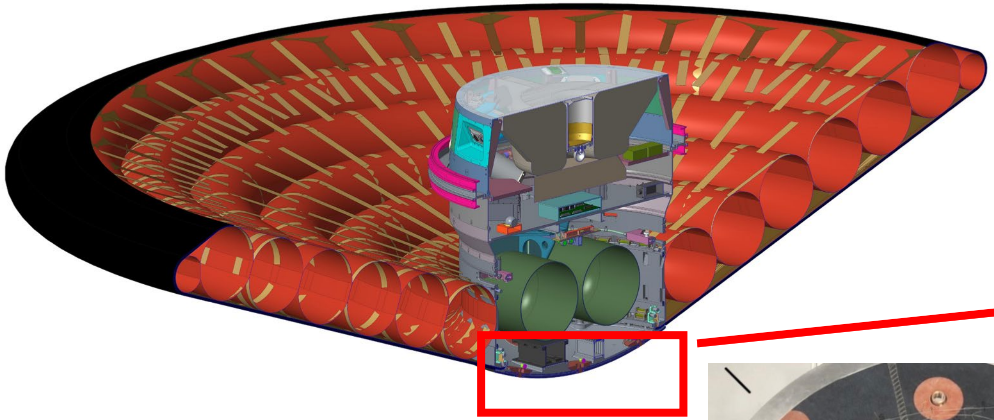


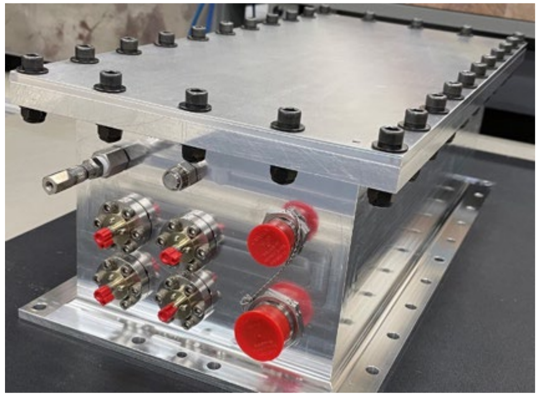


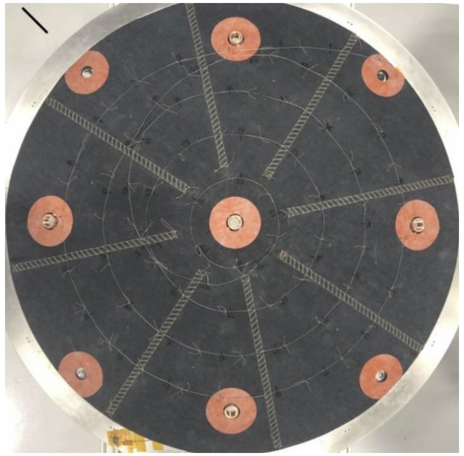


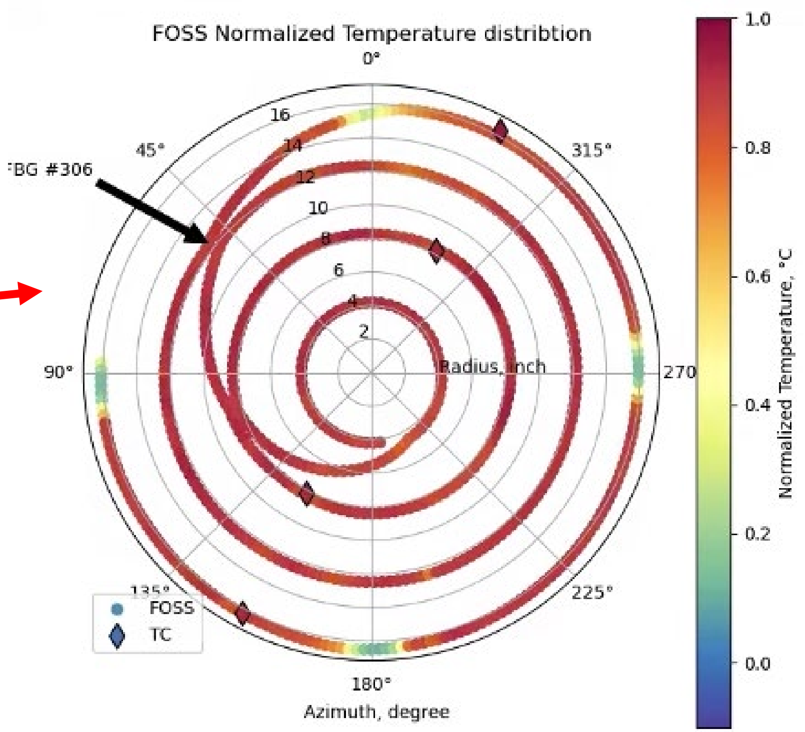


Conclusion









1. Environmental testing of ruggedized FOSS unit has lead to successful implementation into NASA's LOFTID project
2. Testing ensure that FOSS was operating throughout the re-entry process at LOFTID
3. Testing ensure FOSS was able to recording +1000 plus sensors concurrently with high-spatial density temperature measurement throughout re-entry process